

AD A139282

Combustion Science and Technology, 1983, Vol. 31, pp. 233-247
0010-2202/83 3106-0233\$18.50/0

© 1983 Gordon and Breach Science Publishers, Inc.
Printed in Great Britain

A Model of Freely Burning Pool Fires

C. C. NDUBIZU and D. E. RAMAKER *Department of Chemistry, George Washington University, Washington, D.C.*

P. A. TATEM and F. W. WILLIAMS *Combustion and Fuels Branch, Naval Research Laboratory, Washington, D.C.*

(Received August 12, 1982; in final form November 29, 1982)

Abstract—This paper presents a zone model of liquid pool fires burning in an open environment. The model is a system of coupled non-linear equations which contains physical parameters for which reliable values are not currently available. With a judicious estimate of these parameters, the model was tested on various size fires burning three types of fuel. The predicted results are comparable with experimental results from three groups of earlier workers. Sensitivity analyses were run to determine the relative influence of each estimated parameter on the predicted results. These analyses show that efficiency of combustion in the fire is the most important estimated parameter in this model.

INTRODUCTION

With the rising problem of plane crash fires and accidental fuel spill fires on ships decks, there is need to understand the burning characteristics of these fires in order to develop effective ways of fighting them. This paper presents a simple technique for predicting these characteristics in freely burning pool fires. The majority of existing fire models (e.g., Quintière, 1977; Mitler and Emmons, 1980; Bullen and Thomas, 1979; Satoh *et al.*, 1980) were developed principally to predict these characteristics in confined fires. This is because of the need to establish more effective ways of extinguishing building fires which occur more often and hence cause most of the losses in property and human lives.

Theoretical fire models are often characterized as "field" or "zone" models. Field modeling yields point by point solution of partial differential equations that describe the fire physics. In contrast, the zone model divides the system into sections and solves a set of equations which describes what happens within each section and also the interaction between sections. Hence, in general, zone modeling yields less detailed and less accurate results, although it is an easier technique for obtaining practical solutions. Furthermore, the accuracy of any such solution depends on (a) how well the equations describe what happens within and between zones, and (b) the value of physical parameters (e.g., fuel surface emissivity) contained in the equations. Measured values for some of these parameters are currently not available.

The objectives of this study are (1) to develop a zone model for predicting the steady state characteristics of various liquid pool fires in the open, and (2) to determine through a sensitivity analysis the relative effect of any error in the estimated values of the required physical parameters. The results of this analysis will then serve as a guide for adapting this model for predicting transient characteristics of other fires.

The next section presents the model which comprises a system of non-linear coupled equations which is solved by a hybrid numerical algorithm developed by Powell (1970). With an estimated set of physical parameters, the model was tested on

DTIC FILE COPY

84 03 20 063

various size pool fires. Finally, a sensitivity analysis was undertaken to determine how an error in the estimate of each parameter would affect the predictions of the model.

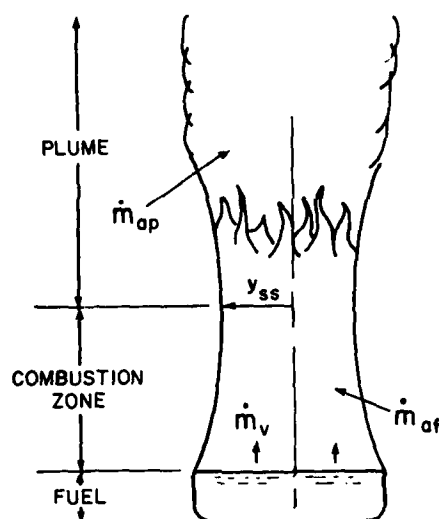


FIGURE 1 Schematic of a liquid pool fire showing the various zones and mass flows.

MATHEMATICAL MODEL

The model considers a liquid pool fire burning freely in a wind-free open environment. The system is divided into three zones; namely, fuel, combustion zone (fire) and plume (see Figure 1). Each zone is assumed to have uniform properties and the model accounts for heat and mass transfer between zones.

The fuel is contained in a circular pan of diameter d , with the liquid level kept constant and flush with the top of the pan. Fuel is assumed to evaporate from the surface at the liquid boiling point, T_b , while the bulk of the liquid remains at T_b . Hence the fuel evaporation rate is

$$\dot{m}_v = \frac{[A_s h_s (T_f - T_s) + \dot{q}_{rs,net}]}{\Delta H_v + C_{fuel} (T_s - T_b)} \quad (1)$$

where $\dot{q}_{rs,net}$ = the net radiant heat gain.† A heat conduction term (Hottel, 1959) has been neglected in Eq. (1). This introduces little error for the pan diameters (> 15 cm) of interest here.

As the fuel vapor rises, it entrains the surrounding air and burns. Part of the heat generated is transferred back to the fuel surface where it is used to evaporate more fuel and thus keep the fire burning. The resulting flame is assumed to be turbulent

†The symbols are explained in the Nomenclature.

with negligible entrainment in the vertical direction. For simplicity the flame is divided into two zones: namely, (a) the combustion zone where all the combustion reactions are assumed to take place, and (b) the plume which is comprised of hot flue gases. Therefore, the heat balance equation in the combustion zone is:

$$\dot{q}_{gen.} = \dot{m}_{af} C_a T_a + \dot{m}_v C_v T_s - \dot{m}_{ss} C_g T_f + A_s h_s (T_f - T_s) = \dot{q}_{rf,net} \quad (2)$$

where the total mass flow out of the combustion zone is

$$\dot{m}_{ss} = \dot{m}_{af} + \dot{m}_v; \quad (3)$$

the heat generated in the fire is

$$\dot{q}_{gen.} = \beta \dot{m}_v \Delta H_c \quad (4)$$

and $\dot{q}_{rf,net}$ = the net radiant heat loss from the fire. Note that a parameter β has been introduced to account for combustion efficiency, i.e., the fraction of the heat of combustion that is actually released in the fire.

The rate of air entrainment into the combustion zone is expressed in terms of height above the fuel surface, H_f , Froude number Fr , heat generation in the fire and properties of the ambient atmosphere (Fang, 1973);

$$\dot{m}_{af} = \dot{m}_v \rho_0'^{-1} \omega \left[\left(0.67 a_f \left(\frac{1 - \omega}{a_f \omega^3 Fr} \right)^{1/5} \frac{H_f}{y_0} + 1 \right)^{5/2} - 1 \right], \quad (5)$$

where

$$\omega = \frac{\bar{M}}{M_a} \left/ \left(1 + \frac{\Delta H_c x_{O_2}}{\gamma C_a T_a} \right) \right. \quad (6)$$

and the normalized density at the fuel surface is

$$\rho_0' = M_{fuel} T_\infty / (29 T_s). \quad (7)$$

Fang (1973) has suggested that the effects of radiation in Eq. (6) be approximated by reducing the value of ΔH_c . Based on the values of radiative heat fraction reported in the literature (e.g., Modak and Croce, 1977), we chose to multiply ΔH_c by a factor of 0.7. Note that Eq. (7) implies that the mass fraction of fuel vapor at the fuel surface is 1. Finally, the remaining terms in Eq. (5) are

$$Fr = \left(\frac{\dot{m}_v}{\rho_v A_s} \right)^2 / g y_0 \quad (8)$$

and

$$H_f = y_0 1.49 \theta_1^{1.5} Z^{2.5}; \quad (9)$$

where

$$\theta_1 = \frac{\omega \left(\frac{\omega}{\rho_0'} + \frac{\gamma}{x_{O_2}} \right)^2}{a_f^4 (1 - \omega)} \quad (10)$$

and the modified Froude number,

$$Z = \rho_0' Fr^{1/2}, \quad (11)$$

Any unreacted fuel and/or oxygen leaving the combustion zone mixes with combustion products and as this hot mixture rises it entrains more of the surrounding air which cools it down. Thus, the energy equation in the plume zone is

$$\dot{m}_{ss} C_g T_f + \dot{m}_{ap} C_a T_a = \dot{m}_p C_p T_p + \dot{q}_{rp,net}, \quad (12)$$

where the total mass leaving the plume is given by

$$\dot{m}_p = \dot{m}_{ss} + \dot{m}_{ap} \quad (13)$$

and $\dot{q}_{rp,net}$ = the net radiant heat loss from the plume. The air entrainment rate in the plume region is given by

$$\dot{m}_{ap} = \frac{\dot{m}_{ss}}{\rho_{ss}'} \left[\left\{ 1.092 \alpha_p \left(\frac{H_p - H_f}{y_{ss}} \right) \left(\frac{(1 - \rho_{ss}')}{\alpha_p F_{ss}} \right)^{1/5} + 1 \right\}^{5/3} - 1 \right], \quad (14)$$

where the density, radius and Froude number of the gas column at the combustion zone/plume interface are, respectively

$$\rho_{ss}' = \frac{\omega \left(1 + \frac{\gamma}{x_{O_2}} \right)}{\frac{\omega}{\rho_0'} + \frac{\gamma}{x_{O_2}}}, \quad (15)$$

$$y_{ss} = y_0 1.19 \left(\frac{\alpha_f Fr}{\omega^{1.5} (1 - \omega)} \right)^{1/5} \left[\frac{(1 + \gamma/x_{O_2})^5}{\frac{\omega}{\rho_0'} + \gamma/x_{O_2}} \right]^{1/10} (\rho_0')^{2/5} \quad (16)$$

and

$$F_{ss} = \left(\frac{\dot{m}_{ss}}{\rho_{ss}' \rho_a \pi} \right)^2 / g y_{ss}^5, \quad (17)$$

Furthermore, Fang's analysis has shown that the visible flame height correlates reasonably well with the point on the plume axis where the temperature, T_t , falls down to about 700°K. Presently, the current model uses Fang's expression for the flame height, thus,

$$H_p = y_0 (1.49 + 0.916 \theta_2^{1.5}) \theta_1^{1/5} Z^{2.5}, \quad (18)$$

where

$$\theta_2 = \frac{\left(\frac{\alpha_f}{\alpha_p}\right)^4 (1 - \omega) \left\{ \left[\frac{\omega(1 - \rho_0')}{\rho_0'} + \frac{\gamma(1 - \omega)}{X_{O_2}} \right] \frac{T_l}{T_x} + \frac{\omega(\rho_0' T_0' - 1)}{\rho_0'} \right\}^3}{\omega^3 \left(\frac{\omega}{\rho_0'} + \frac{\gamma}{X_{O_2}} \right)^3 (1 - \rho_{ss'}) \left(\frac{T_l}{T_x} - 1 \right)^3} \quad (19)$$

and

$$T_0' = \frac{T_s}{T_x}; \quad T_l \approx 700^\circ \text{K}. \quad (20)$$

However, other expressions for flame height (e.g., Zukoski, 1981) can equally be used in the model.

Finally, the net radiant heat transfer between the three zones is derived by making the following assumptions:

a) The combustion zone and plume, each is a grey absorbing and emitting medium with homogeneous properties.

b) Emissivity, ϵ , is given by

$$\epsilon = 1 - e^{-\kappa L_m}; \quad (21)$$

where the mean beam length is expressed as (Orloff, 1980)

$$L_m = \frac{3.6 V}{A} \quad (22)$$

and κ is the absorption coefficient.

c) The volumes of the combustion zone and the plume are approximated by frustrums of right cones, with dimensions obtained from Fang's analysis.

d) Transmissivity of the fuel surface is zero.

Thus, the radiant heat transfer at the fuel surface, in the combustion zone and in the plume are given, respectively by (Eckert and Drake, 1972),

$$\dot{q}_{rx,net} = \frac{A_s \epsilon_s}{1 - \epsilon_s} [B_s - e_{bs}]; \quad (23)$$

$$\dot{q}_{rf,net} = A_s \epsilon_f (e_{bf} - B_s) + A_f \epsilon_f (e_{bf} - e_{ba}) + A_p' \epsilon_f (e_{bf} - e_{bp}) \quad (24)$$

and

$$\dot{q}_{rp,net} = A_p' \epsilon_p (e_{bp} - \epsilon_f e_{bf} - B_s \tau_f F_{sp}) + (A_p + \pi y_p^2) \epsilon_p (e_{bp} - e_{ba}); \quad (25)$$

where

$$e_b = \sigma T^4 \quad (26)$$

is the black body emissive power:

$$B_s = \epsilon_s e_{bs} + (1 - \epsilon_s) \{ \epsilon_f e_{bf} + \tau_f [\epsilon_p e_{bp} F_{sp} + e_{ba} (1 - F_{sp})] \} \quad (27)$$

is the fuel surface radiosity and the view factor between the plume and surface is

$$\bar{F}_{sp} = 0.5 \left[\frac{H_f + 1}{y_{ss}^2} + 1 - \left\{ \left[\frac{H_f^2 + 1}{y_{ss}^2} + 1 \right]^2 - \frac{4}{y_{ss}^2} \right\}^{1/2} \right]. \quad (28)$$

Furthermore, the radius of the top of the plume is given by

$$y_p = 1.2\alpha_p(H_p - H_f) + y_0 1.1\theta_3^{1/5} Z^{2/5}, \quad (29)$$

where

$$\theta_3 = \frac{\alpha_p \left(\frac{\omega}{\rho_0'} + \frac{\gamma}{x_{O_2}} \right)^2}{\omega^2 (1 - \rho_{ss}')}. \quad (30)$$

Finally, the areas of the plume surface, the lateral surface of the combustion zone and the plume/fire interface are given, respectively by

$$A_p = \pi(y_{ss} + y_p)[(H_p - H_f)^2 + (y_p - y_{ss})^2]^{1/2}; \quad (31)$$

$$A_f = \pi(y_0 + y_{ss})[H_f^2 + (y_0 - y_{ss})^2]^{1/2} \quad (32)$$

and

$$A_p' = \pi y_{ss}^2. \quad (33)$$

NUMERICAL SOLUTION

The system of non-linear algebraic equations derived in the previous section can be put in the form

$$f_i(x_1, x_2, \dots, x_n) = 0, \quad i = 1, 2, \dots, n. \quad (34)$$

The set was then solved using a computer algorithm developed by Powell (1970). This algorithm is a variation of the classical Newton-Raphson iteration such that its fast convergence is maintained, while the problems which arise in the iteration when the Jacobian becomes singular or when starting from a poor initial guess of the solution are avoided.

The current computer code was written such that only three equations [Eqs. (1), (2) and (12)] in the set are actually solved with Powell's algorithm for the three unknowns \dot{m}_v , T_f and T_p . However, at each iteration current values of \dot{m}_v , T_f and T_p are used to evaluate the rest of the equations. This is equivalent to solving these equations exactly at each iteration. This arrangement is possible because one can in principle write the above three equations explicitly in terms of \dot{m}_v , T_f and T_p using the other equations. This technique saved considerable computer time.

In addition to the initial guess of the solution of the system of equations, Powell's algorithm requires the user to supply other numerical parameters; the key ones being the initial iteration step size and a convergence criterion. The iteration is said to converge when

$$\sum_{k=1}^n [f_k(x_1, x_2, \dots, x_n)]^2 \leq \mu. \quad (35)$$

In the double precision version of the current code where $n = 3$, μ was set equal to 10^{-10} .

RESULTS AND DISCUSSION

The model has been tested on gasoline, kerosene and methanol pool fires of various sizes. Pan diameter was varied between 15 and 200 cm, a range which covers various stages of turbulence in the fire. The properties of the three fuels used in the calculations are given in Table I. One recognizes that gasoline and kerosene are both variable mixtures of hydrocarbons and hence their properties will depend on the mixture. However, for the purpose of this work, handbook (Bolz and Tuve, 1976) values of these properties have been used.

Table II lists the estimated values of the physical parameters for the three liquid pool fires. These estimates are close to the values used in related works (Quintière,

TABLE I
Properties of the fuels used

Property	Fuel		
	Gasoline	Kerosene	Methanol
Specific heat (liquid), C_{fuel} W-sec/kg $^{\circ}$ K	2364	2090	2540
Boiling point, T_b $^{\circ}$ K	410.8	499.67	337.8
Stoichiometric air/fuel ratio	14.97	14.99	6.47
Heat of combustion, ΔH_c W-sec/kg	4.39×10^7	4.30×10^7	2.23×10^7
Heat of vaporization, ΔH_v W-sec/kg	2.696×10^5	2.0×10^5	11×10^5
Molecular weight, M_{fuel}	126	154	32
Liquid density at boiling point, kg/m 3	684.1	740.2	786.5

TABLE II
Best estimate of the various parameters

Parameter	Value used for gasoline and kerosene fires	Value used for methanol fire
β	0.73	0.95
ϵ_s	0.42	0.42
h_s (W/m 2 $^{\circ}$ K)	2.5	2.5
M/M_a	3.0	1.0
κ_f (m $^{-1}$)	1.05	0.85
κ_p (m $^{-1}$)	0.75	0.35
α_f	0.25	0.25
α_p	0.15	0.15

1977; Mitler and Emmons, 1981; Markstein, 1978) and they were tested by comparing predicted fire characteristics with measured values (Blinov and Khudiakov, 1957). Note that the values of some of the parameters for methanol fire (Table II) are different from similar values for kerosene and gasoline fires. In general, methanol fires burn cleaner than kerosene or gasoline fires of the same size. Consequently, β for the methanol fire was estimated close to 1.0 while absorption coefficients were estimated lower than the values for gasoline and kerosene fires. In addition, the molecular weight of methanol is nearly equal to that of air, hence the normalized average molecular weight in the methanol fire was estimated to be 1.0.

One would expect some of these physical parameters to vary with pan size. In fact, recent work by Markstein (1978) suggests that the average fire temperature would vary inversely with pan size, while the absorption coefficient would increase with pan size. Also in a recent paper by Tewarson *et al.* (1980) it was reported that for small size fires ($d = 10$ and 30 cm) the combustion efficiency does not vary appreciably with d . Although this conclusion is consistent with the current work, one would expect that over a wider range of pan size, β would vary inversely with d . These effects probably result from inefficiencies such as soot formation, etc. However, since it is not known exactly how these parameters vary with pan size, β and \bar{M}/M_a were allowed to vary in this work (for $d \geq 100$ cm) in order to obtain results that are comparable to measured values. Hence, for pan diameters greater than 100 cm, β was decreased to 0.64 while \bar{M}/M_a was increased to 4.0. One could equally increase κ_f for large fires to improve the results.

Table III compares the predicted characteristics of three 30 cm diameter liquid pool fires (methanol, gasoline and kerosene) with the same characteristics measured by three independent groups, namely Blinov and Khudiakov (1957), Rasbash *et al.* (1956) and Burgess *et al.* (1959). The fuel evaporation velocity, v_0 , is the rate at which the liquid level would fall if it was not maintained flush with the top of the pan. Table III reveals that with the given values of the physical parameters, the current model predicts the characteristics of unconfined fires reasonably well.

Next, the model was further tested by applying it to kerosene and gasoline pan fires of base diameters ranging from 15 to 200 cm. The results are summarized in

TABLE III
Comparison of measured and predicted characteristics for 30 cm base diameter liquid pool fires

Source	Fuel	Evaporation velocity v_0 (mm/min)	Temperature of combustion zone T_f K	Visible flame height, H_p , (cm)
This study	Methanol	0.85	1504	74
Rasbash <i>et al.</i>	Methanol	0.99	1491	—
Burgess <i>et al.</i>	Methanol	0.9	—	—
This study	Gasoline	2.6	1351	104
Rasbash <i>et al.</i>	Gasoline	2.3	1299	—
Blinov and Khudiakov	Gasoline	2.5	—	100
This study	Kerosene	1.7	1318	88
Rasbash <i>et al.</i>	Kerosene	1.55	1263	—
Blinov and Khudiakov	Kerosene	1.8	—	—

TABLE IV
Some predicted characteristics of various size fires

Characteristics	Gasoline fires			Kerosene fires		
Pan diameter (cm)	15	50	130	15	50	130
Fuel evaporation rate, kg/m ² -sec	0.018	0.042	0.047	0.012	0.029	0.033
T_f , °K	1395	1325	1165	1353	1294	1135
T_p , °K	525	512	562	522	510	559
\dot{q}_{gen} , kW	10.44	262.8	1771.8	6.4	178.9	1223.0
$\dot{q}_{rf, net}$, kW	2.0	63.5	431.6	1.3	44.6	312.1
$\dot{q}_{rs, net}$, kW	0.13	3.9	31.0	0.089	3.1	25.3
$A_s h_s (T_f - T_s)$, kW	0.04	0.45	2.5	0.038	0.39	2.1
H_p , m	0.5	1.8	3.76	0.41	1.55	3.27
H_f , m	0.18	0.67	1.68	0.15	0.58	1.47
\dot{m}_{af} , kg/sec	0.0069	0.173	1.38	0.004	0.121	0.978
\dot{m}_{ap} , kg/sec	0.034	0.855	4.24	0.021	0.581	2.9

Table IV and also in a v_0 versus d plot (symbols) in Figure 2. The solid lines represent a plot of Blinov and Khudiakov's data. From Figure 2 and Table IV one could deduce that for small pan diameters ($d \leq 50$ cm), the current model does very well in predicting the characteristics of freely burning pool fires. Unfortunately, it does not do as well for large diameter fires ($d \geq 100$ cm). That can be attributed to the following: (a) since the physical parameters were "optimized" for small fires, some of them become less accurate as d increases; (b) the flame shape for large fires is more like a cylinder rather than like two frustrums (see Figure 1) as was assumed in the current model; and (c) the increasing effects of soot particles (e.g., on κ) have not been included in the model.

Table IV presents some of the predicted characteristics of gasoline and kerosene fires of various sizes. Some of these data reveal trends similar to what has been

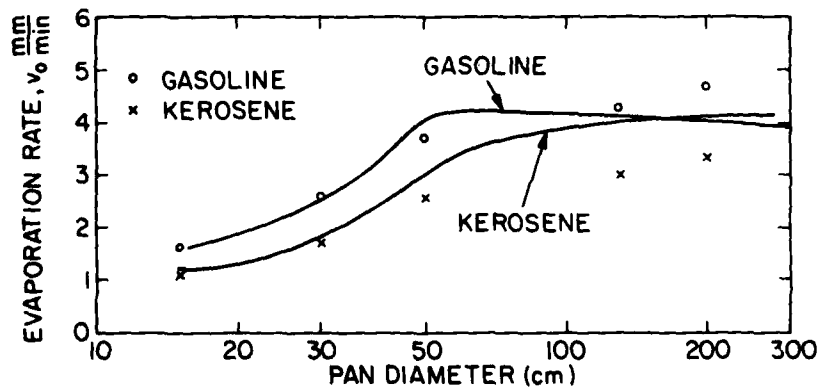


FIGURE 2 Comparison of predicted and measured fuel evaporation rates for various size fires.

observed by earlier investigators. For example, the mass evaporation rate and the ratio of radiative to convective heat transfer to the fuel surface both increase with fire size (Modak and Croce, 1977; Hottel, 1959), while the average fire temperature varies inversely with fire size (Markstein, 1978).

Table IV also shows that the current model predicts visible flame heights which are higher than values reported by Blinov and Khudiakov, especially for large fires. Actually, the visible flame height is a very difficult quantity to measure since the flame is never steady. Hence, it is difficult to say how "inaccurate" the predicted mean heights actually are. However, we expect that the actual mean visible flame height should lie between H_f and H_p .

SENSITIVITY ANALYSIS

As indicated in the previous section the measured values of some of the physical parameters used in the current model are not yet available in the literature. This is because the measurement of these parameters is not only difficult but also places high demands on resources. Consequently, there is need to determine the relative influence of these parameters on the model predictions so as to appropriately allocate resources for measuring them.

A sensitivity analysis was undertaken to determine the relative influence of the following parameters on the model predictions: combustion efficiency, β ; air entrainment coefficients, α_f and α_p ; fuel surface emissivity, ϵ_s ; fuel surface convective heat transfer coefficient, h_s ; normalized mean molecular weight in the fire, \bar{M}/M_a and absorption coefficients κ_f and κ_p . Two methods of sensitivity analysis were used: namely, a "brute force" method (*e.g.*, Ndubizu and Durbetaki, 1978), and a Fourier Amplitude Sensitivity Test (FAST). With the first method, each parameter was varied independently while the rest of the parameters were held constant at their base values. A base value is the best estimate of each parameter (*e.g.*, Table I). For each variation of a parameter a new set of fire characteristics was calculated. Considering the problem of fire spread, the liquid fuel evaporation rate is deemed the key prediction of the current model. Hence, Figure 3 summarizes the results of the analysis in a plot of percent change in parameter versus percent change in fuel evaporation rate.

Using Figure 3, one can rank the various parameters in their order of importance in influencing the predicted value of the fuel evaporation rate. This ranking would be: combustion efficiency, fuel surface emissivity, fire absorption coefficient, normalized mean molecular weight of species in the fire, air entrainment coefficient in the combustion zone, fuel surface convective heat transfer coefficient, and finally absorption coefficient and air entrainment coefficient in the plume. It is interesting to note that the parameters for the plume have no measurable effect on the predicted fuel evaporation rate. This is expected, considering the low temperatures in the plume and the view factor between the plume and the fuel surface.

The main drawback of the above "brute force" method is the assumption that the parameters are independent and, hence, that they can be varied one at a time. This drawback is avoided in the FAST method developed by Cukier *et al.* (1973) [also see Cukier *et al.* (1975)]. With this method, the parameters $\lambda_i (i=1, 2, \dots, n)$ are varied simultaneously through the introduction of a variable, s , such that

$$\lambda_i = \lambda_i^{(0)} e^{u_i s} \quad (36)$$

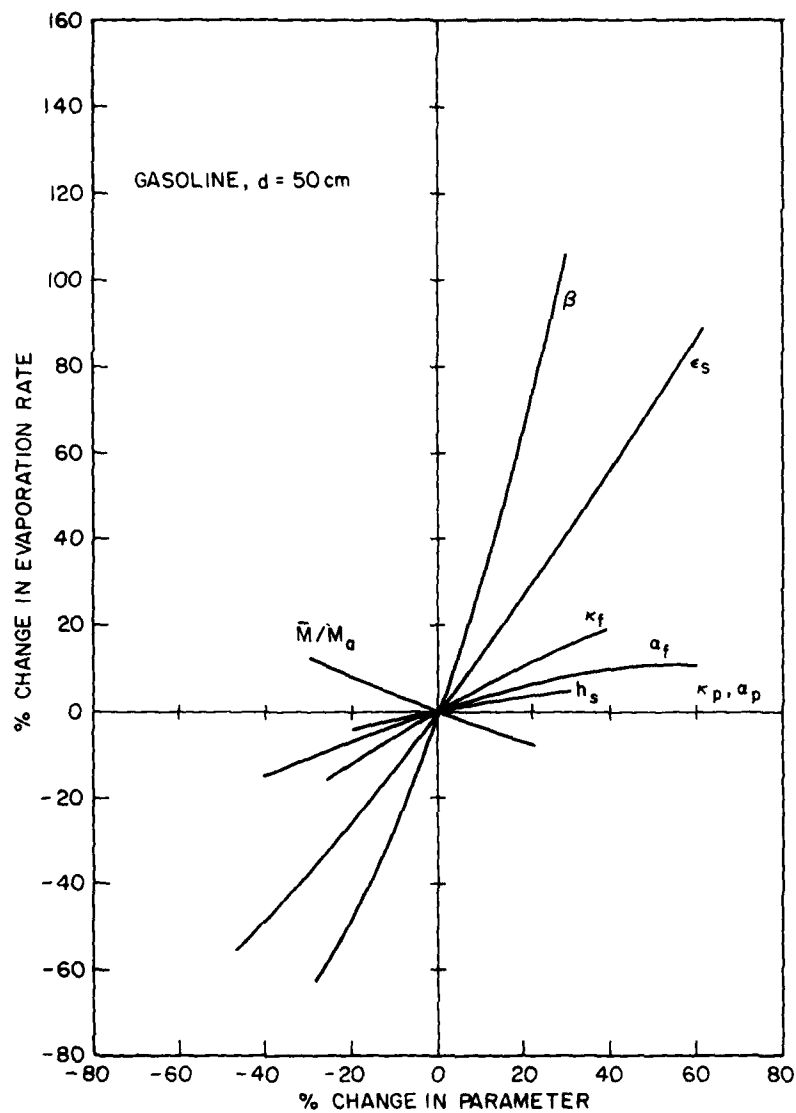


FIGURE 3 Sensitivity of the various parameters on fuel evaporation rate.

where

$$u_i = u_i^{(0)} \sin \psi_i s. \quad (37)$$

$\lambda_i^{(0)}$ is the best estimate of λ_i (e.g., Table I). The frequency ψ_i is a positive integer and $u_i^{(0)}$ is the uncertainty on λ_i which defines the range between which λ_i is varied.

Thus the predicted characteristics (*e.g.*, \dot{m}_r) are periodic functions of s with period 2π . Each characteristic is then Fourier analyzed and the Fourier coefficient for each frequency corresponds to the sensitivity (to the characteristic) of the parameter to which that frequency was assigned. Hence,

$$\Phi_{ij} = \frac{2}{N} \sum_{j=1}^N \dot{m}_r(s_j) \sin \phi_j s_j; \quad i = 1, 2, \dots, n, \quad (38)$$

where

$$s_j = 2\pi j/N, \quad j = 1, 2, \dots, N. \quad (39)$$

The frequencies (1, 21, 31, 37, 45, 49) and $N = 182$ used in the current analysis are obtained from the work of Shaibly and Shuler (1973). Assignment of frequencies to the various parameters was arbitrary. However, a different permutation of the frequencies did not change the conclusions drawn from this analysis (Shaibly and Shuler, 1973). The uncertainty, $u^{(0)}$, for each parameter was chosen as 0.3. In this way, all the parameters varied within ranges that are physically possible. For example, β varied between 0.99 and 0.54 for a 30 cm diameter pan gasoline fire.

Table V presents the results of the sensitivity analysis using the FAST method. For a given fire size, the relative magnitude of the coefficients depicts the sensitivities of the various corresponding parameters on \dot{m}_r . Incidentally, the magnitude of the coefficients in the two fires should not be compared; the different magnitudes result from the definition of ϕ in Eq. (38). Thus, Table V shows that β is the most sensitive while h_s is the least sensitive parameter in both the large and small size fire. In fact, for a small size fire ($d = 30$ cm), Table V can be used to rank the parameters in exactly the same order as was obtained with the "brute force" method. This suggests that for small size fires the various parameters may be assumed independent to a good approximation.

TABLE V
Coefficients for the sensitivity of the various parameters on fuel evaporation rate

Parameter	Coefficient $d = 30$ cm	Coefficient $d = 130$ cm
Combustion efficiency, β	7.3	212.7
Fuel surface emissivity, ϵ_s	3.4	106.4
Fire absorption coefficient, κ_f	1.54	34.68
Normalized molecular weight, $/M_a \bar{M}$	- 0.95	- 36.75
Air entrainment coefficient, a_f	0.71	26.3
Convective heat transfer coefficient, h_s	0.48	7.08

Considering the feedback mechanism which controls the physics of liquid or solid fuel fires, it is not surprising that the parameters which govern the amount of heat liberated in the fire, (β) and the amount fed back to the fuel (ϵ_s) should be the controlling parameters in this model. Recall from Table IV that radiation is the principal mode of heat transfer to the fuel surface. Furthermore, both methods revealed the

inverse relationship between the normalized mean molecular weight in the fire with the fuel evaporation rate. For a given fuel and pan size, increase in \bar{M}/M_a means increased proportion of higher molecular weight species in the fire. This leads to a reduced T_f and consequently reduced \dot{m}_v .

Finally, the results of the sensitivity analyses suggest that experimentalists ought to give priority to the measurement of the efficiency of combustion in the fire rather than any other unknown parameter needed in fire models. In fact, Emmons (1978) in a recent paper, has indicated the need to measure this parameter. Unfortunately, this may not be an easy task since one would expect the efficiency of combustion in the fire to depend on (among other things) the properties of the fuel (Tewarson *et al.*, 1980), the chemistry of combustion in the particular fire and turbulence.

CONCLUSIONS

A zone model has been developed to predict the characteristics of liquid pool fires in the open. This model includes several physical parameters, values of which have not yet been measured. With a judicious estimate of these parameters, the model was shown to predict results which are comparable with measured values. Sensitivity analyses were run to determine the relative influence of the various (estimated) parameters on the predicted results. These analyses show that the combustion efficiency in the fire is the most critical estimated parameter in the model.

Finally, with the current estimate of these parameters, the model can now be adapted to predict transient characteristics of pool fires in a completely sealed enclosure where the effects of oxygen depletion and pressure build-up are very important.

NOMENCLATURE

A	area (m^2)
B	radiosity
C	specific heat at constant pressure ($W\text{-sec/kg}\cdot K$)
d	diameter of fuel container (m)
	fire base diameter
e_b	black body emissive power
\bar{F}	view factor
Fr	Froude number (Eq. 8)
Fr_{ss}	Froude number (Eq. 17)
g	acceleration due to gravity (m/sec^2)
h_s	convective heat transfer coefficient ($W/m^2\cdot K$)
ΔH_v	latent heat of vaporization of the fuel ($W\text{-sec/kg}$)
ΔH_c	heat of combustion of the fuel ($W\text{-sec/kg}$)
H	height (m)
L_m	mean beam length (Eq. 22)
M	molecular wt
\bar{M}	average molecular weight of species in the fire
\dot{m}	mass flow rate (kg/sec)
\dot{m}_v	fuel evaporation rate (kg/sec)
\dot{q}	power (W)

THIS
COPY
APPROVED

Accession For	
NTIS GRA&I	
DTIC TAB	
Unannounced	
Justification	
By	
Distribution/	
Availability Codes	
Dist	Avail and/or Special
A-121	

\dot{q}_{gen}	$\beta \dot{m}_r \Delta H_c$
s	parameter (Eq. 39)
T	temperature ($^{\circ}\text{K}$)
V	volume (m^3)
X_{O_2}	oxygen mass fraction in the air
r	radius (m)
Z	modified Froude number

Greek Symbols

α	entrainment coefficient
β	efficiency of combustion
γ	stoichiometric oxygen/fuel ratio
ϵ	emissivity
θ	defined in Eqs. (10), (19) and (30)
κ	absorption coefficient (m^{-1})
λ	parameter (Eq. 36)
μ	convergence criterion (Eq. 35)
ρ	density (kg/m^3)
σ	Stefan-Boltzman constant ($\text{W}/\text{m}^2 \text{ } ^{\circ}\text{K}$)
τ	transmissivity
Φ	Fourier coefficient (Eq. 38)
ψ	frequency
ω	defined in (Eq. 6)

Subscripts

a	environmental air
b	fuel
c	combustion
f	combustion zone
p	plume zone
r	radiation
s	fuel surface
sf	combustion zone—plume interface
t	flame tip
v	vapor
O_2	oxygen
fuel	fuel
0	flame-fuel interface
∞	ambient conditions

Superscripts

0	base value
---	------------

ACKNOWLEDGEMENTS

Two of us (C. C. Ndubizu and D. E. Ramaker) acknowledge the partial support of this work by the Naval Research Laboratory.

REFERENCES

- Blinov, V. I., and Khudiakov, G. N. (1957). Certain laws governing the diffusive burning of liquids. *Academiia Nauk, SSR Doklady*, **113**, 1094-1098.
- Bolz, R. E., and Tuve, G. L. (Eds.) (1976). *Handbook of Tables for Applied Engineering Science*. CRC Press, Cleveland, Ohio.
- Bullen, M. L., and Thomas, P. H. (1978). Compartment fires with non-cellulosic fuels. *Seventeenth Symposium (International) on Combustion*, The Combustion Institute, pp. 1139-1148.
- Burgess, D. S., Grumer, J., and Wolfhard, H. S. (1959). Burning rates of liquid fuels in large and small open trays; in Berl, W. G. (Ed.), *The Use of Models in Fire Research*. Publication 786 National Academy of Science, NRC Washington, D.C., 1961.
- Cukier, R. I., Fortuin, C. M., Shuler, K. E., Petschek, A. G., and Schaibly, J. H. (1973). Study of the sensitivity of coupled reaction systems to uncertainties in rate coefficients. I. Theory. *J. Chem. Phys.* **59**, 3873.
- Cukier, R. I., Shaibly, J. H., and Shuler, K. E. (1975). Study of the sensitivity of coupled reaction systems to uncertainties in rate coefficients. III. Analysis of the approximations. *J. Chem. Phys.* **63**, 1140.
- Eckert, E. G., and Drake, R. M. (1972). *Analysis of Heat and Mass Transfer* (McGraw-Hill, New York), p. 671.
- Emmons, H. W. (1978). The prediction of fires in buildings. *Seventeenth Symposium (International) on Combustion*. The Combustion Institute, p. 1101.
- Fang, J. B. (1973). Analysis of the behavior of freely burning fire in a quiescent atmosphere. NBSIR-73-115, National Bureau of Standards, Washington, D. C.
- Hottel, H. C. (1959). Certain laws governing diffusive burning of liquids—A review. *Fire Res. Abs. Rev.* **1**, 41-44.
- Markstein, G. H. (1978). Radiative properties of plastic fires. *Seventeenth Symposium (International) on Combustion*. The Combustion Institute, p. 1053.
- Mitler, H. E., and Emmons, H. W. (1981). The fifth Harvard computer fire code. Home Fire Project Technical Report No. 45.
- Modak, A. T., and Croce, P. A. (1977). Plastic pool fires. *Combustion and Flame* **30**, 251-265.
- Ndubizu, C. C., and Durbetaki, P. (1978). Modeling radiative ignition of fabrics in air. *Fire Research J.*, 281-190.
- Orloff, L. (1980). Simplified radiation modeling of pool fires. *Eighteenth Symposium (International) on Combustion*. The Combustion Institute, p. 549.
- Powell, M. J. D. (1970). A Fortran subroutine for solving system of nonlinear algebraic equations; in Rabinowitz, P. (Ed.), *Numerical Methods for Non-linear Algebraic Equations*, Gordon and Breach, N.Y., Chap. 7, p. 115.
- Quintière, J. (1977). Growth of fire in building compartments; in Robertson, A. F. (Ed.), *Fire Standards and Safety*, ASTM STP 614, p. 131.
- Rasbash, D. J., Rogowski, Z. W., and Stark, G. W. Y. (1956). Properties of fires of liquids. *Fuels* **35**, pp. 94-107.
- Satoh, K., Lloyd, J. R., and Yang, K. T. (1980). Turbulent buoyant flow and smoke layers in a 2-D rectangular compartment with vertical vents. Presented at Fall Technical Meeting, Eastern Section, Combustion Institute, Princeton University, Princeton, N.J.
- Schaibly, J. H., and Shuler, K. E. (1973). Study of the sensitivity of coupled reaction systems to uncertainties in rate coefficients. II. Application. *J. Chem. Phys.* **59**, 3879.
- Tewarson, A., Lee, J. L., and Pion, R. F. (1980). The influence of oxygen concentration on fuel parameters. *Eighteenth Symposium (International) on Combustion*, The Combustion Institute, p. 563.
- Zukoski, E. E., Kubota, T., and Cetegen, B. (1981). *Entrainment in the Near Field of Fire Plumes*, California Institute of Technology.